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Dynamic Investigation of Thermal Behavior in a Hot Water Storage Tank

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ABSTRACT

Air Source Heat Pump Water Heater is an environmental –friendly technology with high efficiency. The thermal behavior of water in the storage tank has great importance for designing a more energy-saving control strategy. In this study, the time-dependent temperature distributions during typical transient processes including heating up and tapping processes are studied with a 3D CFD model of the water storage tank in a cyclic heat pump water heater. The simulated temperature profiles in the heating up period were in good agreement with the experimental results. Different initial conditions were tested in the heating up periods, and they had little influence on the final temperature profiles in a practical water tank. The influences of varied flow rates and supply water temperatures were studied in the tapping stages. The thermocline was shortened when the temperatures in the bottom were higher and the flow rates were larger. Finally, the possibility to calculate the flow rates from the temperature changes was discussed.

1. INTRODUCTION

Hot water has become one of the main heat consumptions in residential sectors. Usually, the air source heat pump water heater (ASHPWH) has a higher efficiency than the electric water heater and gas water heater, so it is seen as an environmental-friendly technology. The water tank is a main component in the ASHPWH system and the thermal behaviors of water has great importance on the system's efficiency.

A lot of previous works have studied the temperature profile in the water tank. Except for different inlets and shapes, such as the equalizer fixed to the inlet and rectangular tanks, the most common tank were cylinders and the influences of the inlet tubes were neglected so that the 1-D model could be applied to predict the thermal behaviors during charging and discharging processes, being often applied in commercial software, such as TRNSYS. 1-D model was faster and easier to simulate, but it was not always available since the flow in the water tank sometimes could be so complex that the temperature profiles perpendicular to the flow direction were not uniform, especially in the stand-by process.

This paper studied the heating up periods and tapping processes by the 3-D model of a practical cylinder water tank. Different initial conditions of the heating up periods were simulated under the same system controlling strategy. The tapping processes included several flow rates and supplied water temperatures.

2. PHYSICAL MODELS

The water tank model was derived from the one in experimental study, as shown in Figure 1. The tank volume is 185L with a height of 1786mm, and the external surface was insulated with foam material whose thermal conductivity was less than 0.02W/m·K. The inner diameters of its 3 connecting tubes stretched into the tank were 14.4mm, with Φ5mm holes near the outlets. The tube, through which the water was pumped into the tank after heated, was jointed but did not insert into the tank. Six thermocouples were installed to measure the temperature distributions in the tank. The distances between them and the bottom are 1409, 1259, 1114, 899, 661, and 456, respectively (unit: mm). Moreover, a mass flow meter was used to measure the cyclic and tapping flow rates.

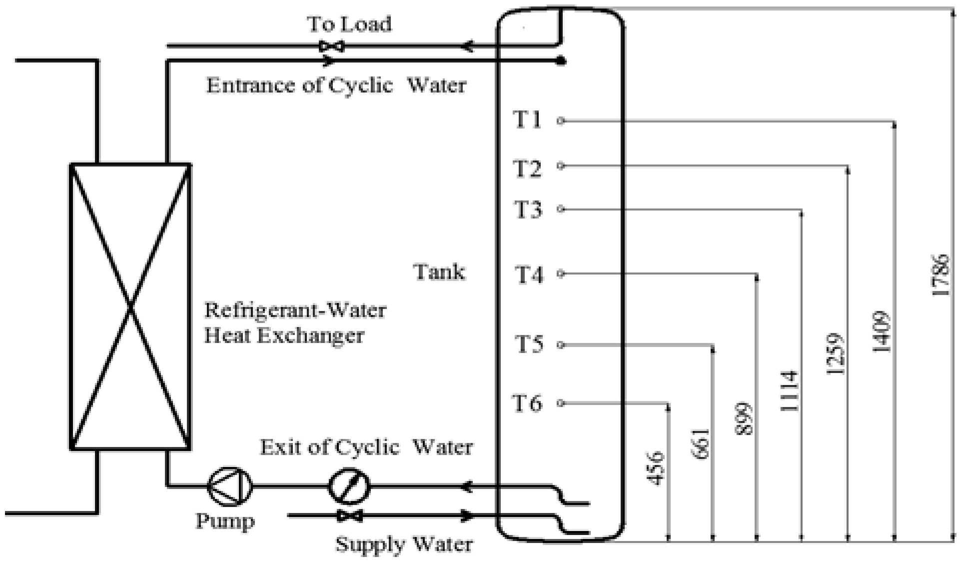


Figure 1: The schematic of the water heating unit

3. CFD MODEL DESCRIPTION

The temperature distribution in the water tank was modeled using the commercial finite volume CFD solver ANSYS. Integrated solver and implicit scheme were used to provide 3-dimensional unsteady state computation. RNG k-ε model was applied since the inlet turbulence was considerable though the average velocity in the vertical direction was quite small. The pressure-velocity was coupled using SIMPLE model. The governing equations were discretised using the 2nd order upstream scheme. Properties of water were defined as the piecewise-linear functions of the temperature, checking interpolating the data from NIST database.
The mesh was generated with Hex/Wedge and Tri, and the grid independency had been tested. The final mesh used in the simulation was 864,202 cells.
The boundary conditions were set according to controlling strategies of the air source heat pump and the Chinese National Standard GB/T 23137-2008. During the heating up period, the heating power from the refrigerant-water heat exchanger was 3500W; water was heated until the temperature of water pumped out of the tank reached 39ºC; and the flow rate was adjusted to keep the temperature of water after heating constant as the setting temperature, 55ºC. During the tapping process, the water supplied into the tank kept constantly 9ºC and 25ºC in different cases and the flow rates were 100~700L/h.
The flow rate during the heating up period was defined by UDFs as following:

$$Qv(t_{out},\tau)=\begin{cases}\dfrac{Q}{c_p\rho(t_{setting}-t_{out}(\tau))} & t_{out}(\tau)<39^{o}C\\ 0 & t_{out}(\tau)\geq 39^{o}C\end{cases}$$

The effects of initial conditions were studied in this paper and they would be introduced in the results.

4. RESULTS AND DISCUSSIONS

4.1 Heating Up Periods

The heating up periods with different initial conditions were simulated to find out the influence of the initial temperature profiles, as shown in Figure 2. Case 1 was conducted with a slightly linear temperature profile, which was the same with the experimental initial condition; Case 2 simulated the reheating stage after tapping for 12.6 minutes at a 7.33L/min flow rate and the supply water temperature was 25.2ºC; Case 3 started with the condition that tapping lasted for 36.7 minutes at a 3.33L/min flow rate and the supply water temperature was 25°C; the initial condition of Case 4 was similar with Case 3, however, its supply water temperature was 9°C.

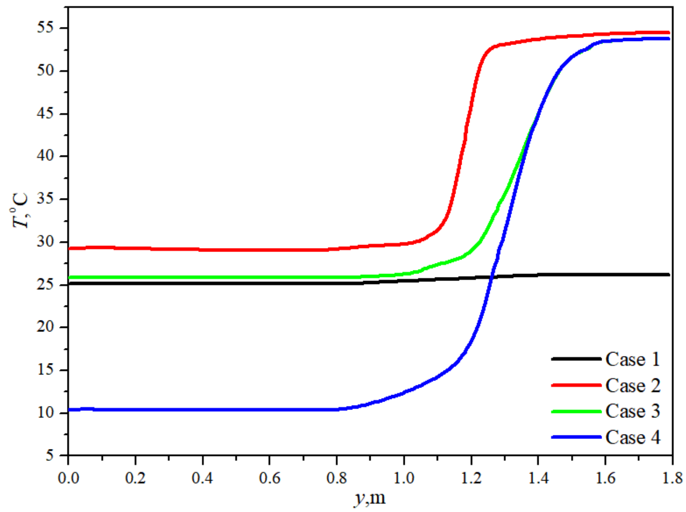


Figure 2: Initial temperature profiles of heating up periods

Figure 3 showed the good agreement between the simulation and the experiment results of Case 1, where the solid lines represented for simulation results and the scatters represented the experimental ones. Several reasons may contribute to the quantitative errors excepted for the measurement accuracy: the CFD model was somehow over-simplified, ignoring the impacts of the blind holes for sensors; and the energy input of the heater in the heat-up stage was rising gradually and fluctuated during the experiment.

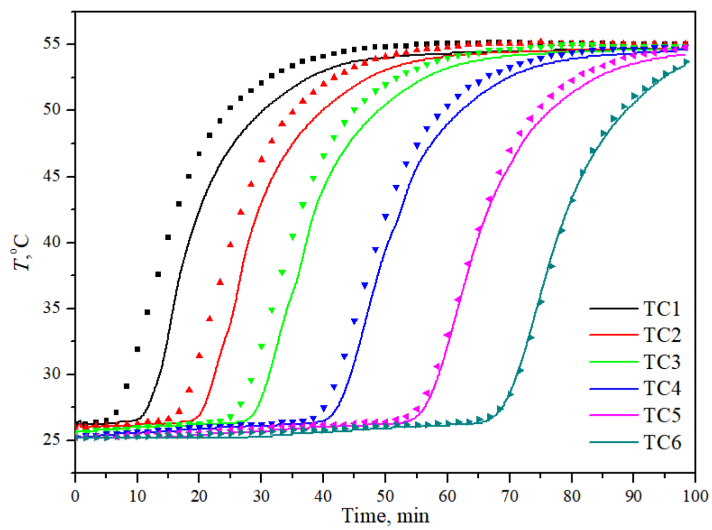


Figure 3: Temperature vs. time during heating up period of Case 1

The temperature profiles when the heating periods finished in different cases were shown in Figure 4. In upper region of the tank, the temperatures in different cases were nearly the same; the deviations appeared in the lower region. It was obviously that the lengths of thermocline in Case 2~4 were almost equal despite the different initial temperature profiles, smaller than Case 1. The thermoclines were commonly used to describe the transition region exists between the hot and cold zones. As it was seen, the widths of thermoclines after tapping and reheating period were smaller than that after first heating, which indicated that the thermoclines were suppressed during the reheating stage. The biggest contributors might be the controlling strategy and the finite volume of the tank. The controlling strategy was designed to limit the flow rate at a reasonable range when the temperature at cyclic outlet rose up, so the heating up periods finished when the temperature at outlet reached 39°C, which indicated that the temperature at a fixed layer in the tank should be 39ºC (point A in Fig.4, beneath the cyclic outlet). However, due to the finite volume of the tank, the conductivity from the upper region to the bottom and the turbulence of the pump resulted in a mixing in the bottom. The increased temperature in the bottom restricted the diffusion of the thermocline; the influence of the initial conditions was reasonably negligible. It should be noticed that the semi-infinite boundary condition was still suitable until the thermocline descended below point A, since the temperature had not started to rise.

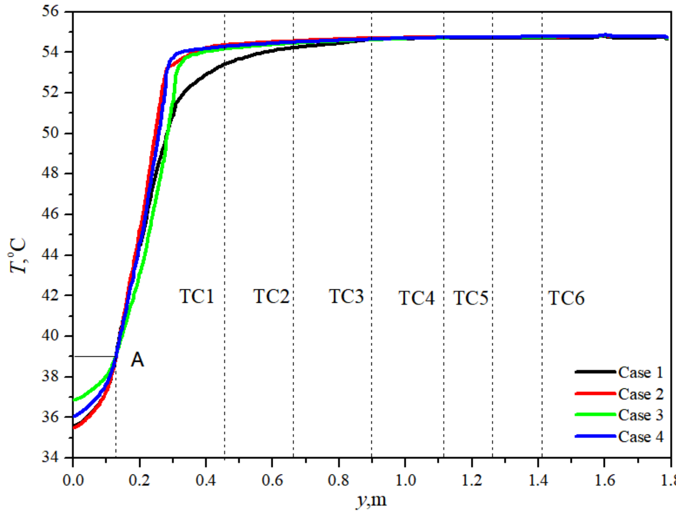
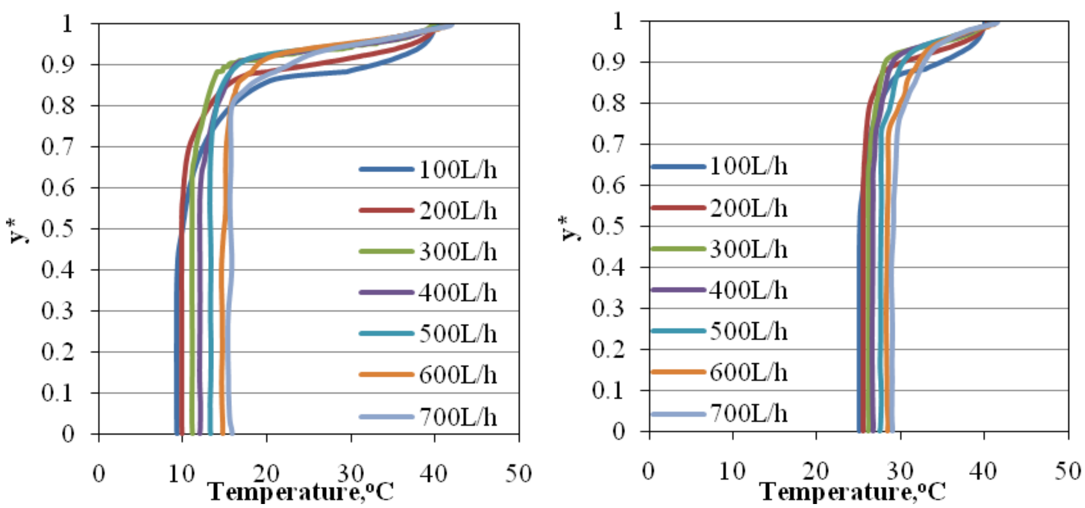


Figure 4: The final temperature profiles in different cases

4.2 Tapping Stages

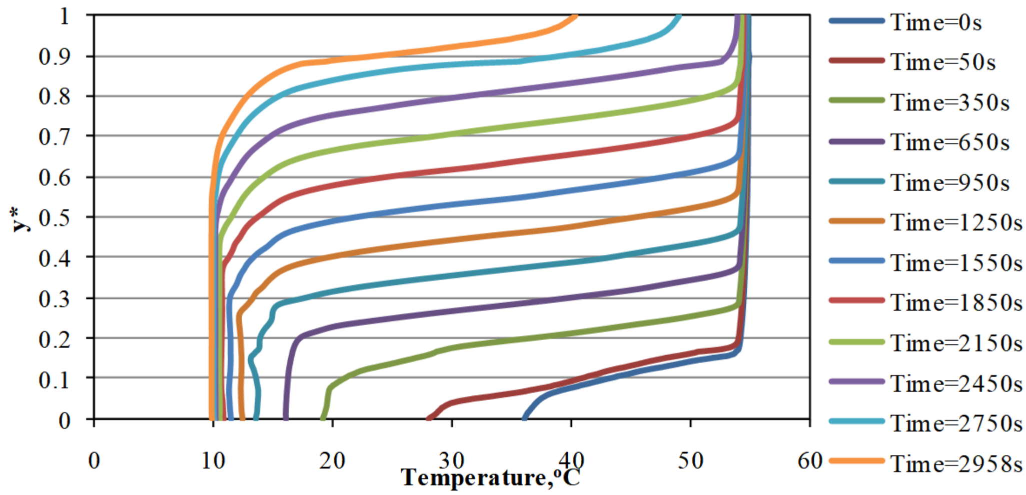
The final temperature profile in Case 3 and Case 4 were used as the initial conditions in tapping stages. Flow rates varied from 100L/h to 700L/h and the supply water temperatures were 9ºC and 25ºC. The final temperature profiles at the end of tapping were shown in Figure 5. The temperature profiles along the vertical axis deviating 20mm from the centre were used to represent those along the vertical direction, avoiding the influence of the connecting tubes. *y** was the normalized height. The different temperatures in the bottom were caused by the injection of the supply water. The faster the cold water injected into the bottom of the tank, the higher the temperature in the mixing zone was, thus the final temperature in the bottom was higher. However, the high flow rates indicated that the tapping time was short and the heat transfer between the hot and cold water was small, so more water with higher temperature were tapped out of the tank. Thermocline regions of supply water temperature 9ºC were larger than those of 25ºC despite the similar initial profiles, due to the lower temperature in the bottom.



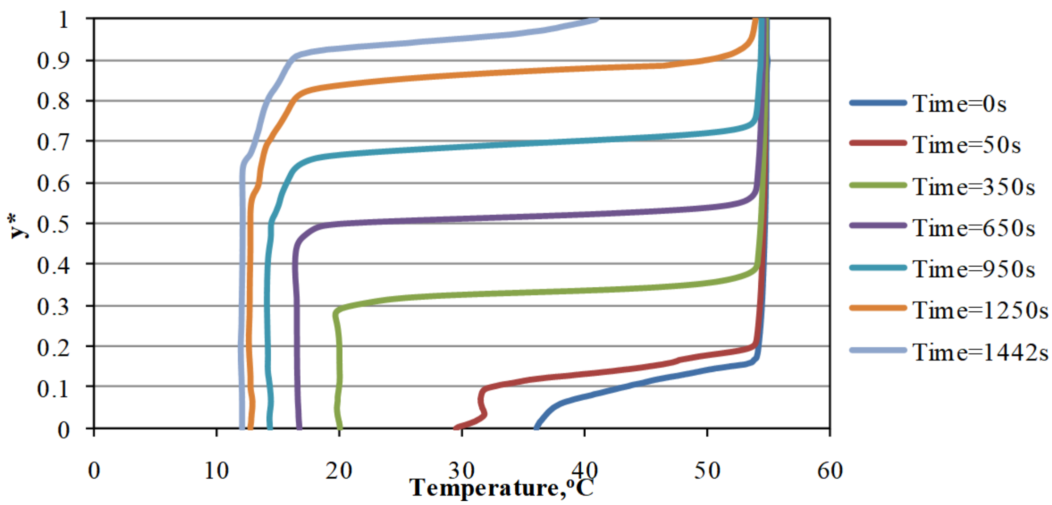
(a) Supply water =9ºC (b) Supply water =25ºC

Figure 5: Temperature profiles at the end of tapping

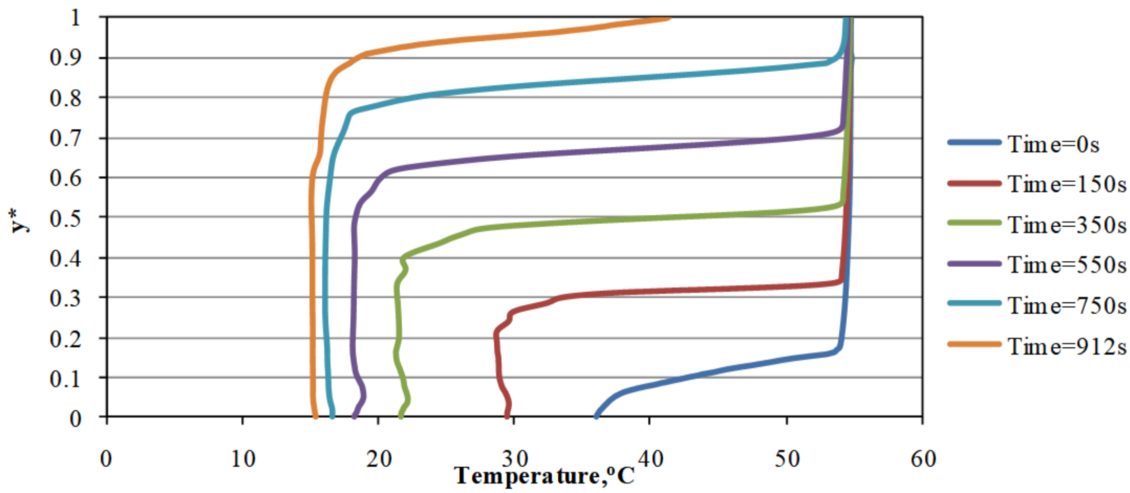
Figure 6 showed temperature changes during the tapping stage. As we could see, the cold supply water injected and mixed with the warmer water in the lower region of the tank, leading the temperature there decreased rapidly at first and then it slowly approached to the supply water temperature. The temperature in the upper region decreased slowly, due to heat loss to the ambient and the disturbance of the injection from the bottom. The influence of the injection was more significant with a larger flow rate. The low flow rate tapping process lasted for a long time, so the thermocline region could enlarge adequately, so the temperature gradient with a lower flow rate was smaller than that with a higher flow rate.



(a) Flow rate=200L/h



(b) Flow rate=400L/h



(c) Flow rate=600L/h

Figure 6: Temperature changes during the tapping stage (supply water =9ºC)

4.3 Discussions

From 4.1 and 4.2, it could be concluded that the initial temperature profile had little influence on the heating up period and tapping stage under the practical system controlling strategy in the real water tank. The important factors were flow rates and supply water temperature. The latter one could be measured by a thermal sensor; however, the former one was rarely measured in the commercial products due to the relatively expensive cost. In the tapping stages, when the thermocline passed, a sharp temperature change would occur, as shown in Figure 7. It was reasonable to attempt to calculate the flow rate from the temperature changes. The distance from TC6 to the bottom could reduce the influence of the injection. The thermoclines were shortened with a high flow rate, and the rate of temperature changes were distinct enough with different flow rates. So, it would be possible to compute the flow rate by the rate of temperature changes. Elementary analysis had been done and the qualitative predictions were acceptable. Further work would be done to obtain a more accurate result for a better prediction of the temperature profiles in the practical tank.

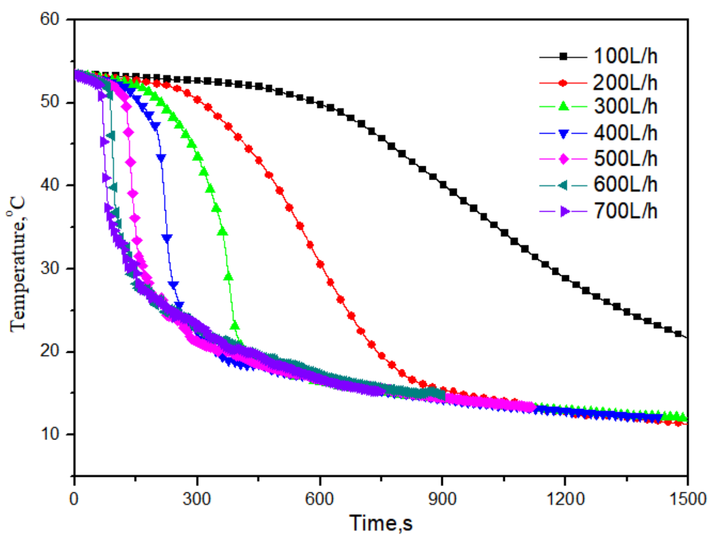


Figure 7: Temperature changes vs. flow rate (TC6, supply water =9ºC)

5. CONCLUSIONS

This paper investigated the thermal behaviors in a practical water tank. A 3-D mode was built to simulate the heating up periods and tapping stages. Different initial conditions were studied, showing a slight influence on the final temperature profiles at the end of heating up period due to the controlling strategy and the finite volume. The flow rates and supply water temperatures had great impacts during the tapping stages. The thermocline was shortened when the temperatures in the bottom were higher and the flow rates were larger. At last, the possibility to calculate the flow rates from the temperature changes was discussed. Further work would be done to predict the flow rates during the tapping stage.

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